1-1-1988

Snowball Garnets Revisited, Southeast Vermont

Rosenfield, J.L.

Christensen, J.N.

De Paolo, D.J.

SNOWBALL GARNETS REVISITED, SOUTHEAST VERMONT[1]

J.L.Rosenfeld, J.N. Christensen, and D.J. DePaolo
University of California

ABSTRACT

In the forensic study of tectonometamorphism, it is difficult to imagine a device better designed to record the sequence of that process' features than a garnet in a schist. With its inclusions, composition, thermoelastic effects around inclusions, and low diffusivities for its constituent ions, that mineral preserves a shell-by-shell record not only of mineral assemblage and fabric sequence but also, with caution because of non-equilibrium effects, of pressure-temperature conditions at time of inclusion. In particular the so-called "snowball" fabric records the syncrystalline rotational motions in terms of their sequence, their directions, and their magnitudes.We now find that the garnet shells also record quantitatively the *rates* (and probably the actual *times*) at which the successive shells accreted in the form of a radial increase in their initial $^{87}Sr/^{86}Sr$ values. We will demonstrate at least three major garnet-related tectonometamorphic epochs consisting of: (1) a pre-Acadian poorly documented epoch, possibly pre-Taconic, near the Cambro-Ordovician boundary around an approximately east-west tectonic axis (referred to present geographic coordinates); (2) Acadian nappe formation; and (3) dome and easterly backflow development. We will also deal with the implications of continuing geologic mapping in the area and those of current isotopic studies.

TRIP INFORMATION

The trip will depart promptly from the Keene State College Commons, 8:30 a.m., Saturday, October 15, 1988. **Please sign in so that we don't lose track of you**! We should arrive at Stop 1 on Vermont Route 11, 200 feet west of the pass summit, between Londonderry and North Windham about an hour later. **Participants should provide own sack lunches.** Maximum number of participants is 36. Because some of the trip will involve maneuvering on narrow dirt roads with limited parking space, participants should car (van)-pool to the maximum extent possible! **The trip is a "no-hammer" excursion except for the stop at the Townshend Dam, where excellent samples of snowball garnets are available in road outcrop for unlimited collecting. We'd like to enlist the assistance of all participants in preserving the highly visible minor structural features, thereby enabling future geologists to see them in their field context.**

INTRODUCTION

The trip's primary purpose is to demonstrate the field component of utilization of rotated garnets in interpreting both history and processes for the tectonometamorphic features of southeast Vermont. While the trip route conforms largely to 1972 NEIGC trip 7 (**Figure 1**, modified after Figure 14-1 of Rosenfeld, 1968), new developments affect the way the outcrops are viewed. It is assumed that attendees will have some familiarity with publications bearing on the trip (Rosenfeld, 1968; Bean 1953; Doll et al., 1961; Rosenfeld, 1970; Hepburn et al., 1984; also Rosenfeld and Eaton, 1985).

[1]Isotopic study reported is supported by NSF Grant EAR 87-07356 and UCLA Grant 1601.

Figure 1, B-6

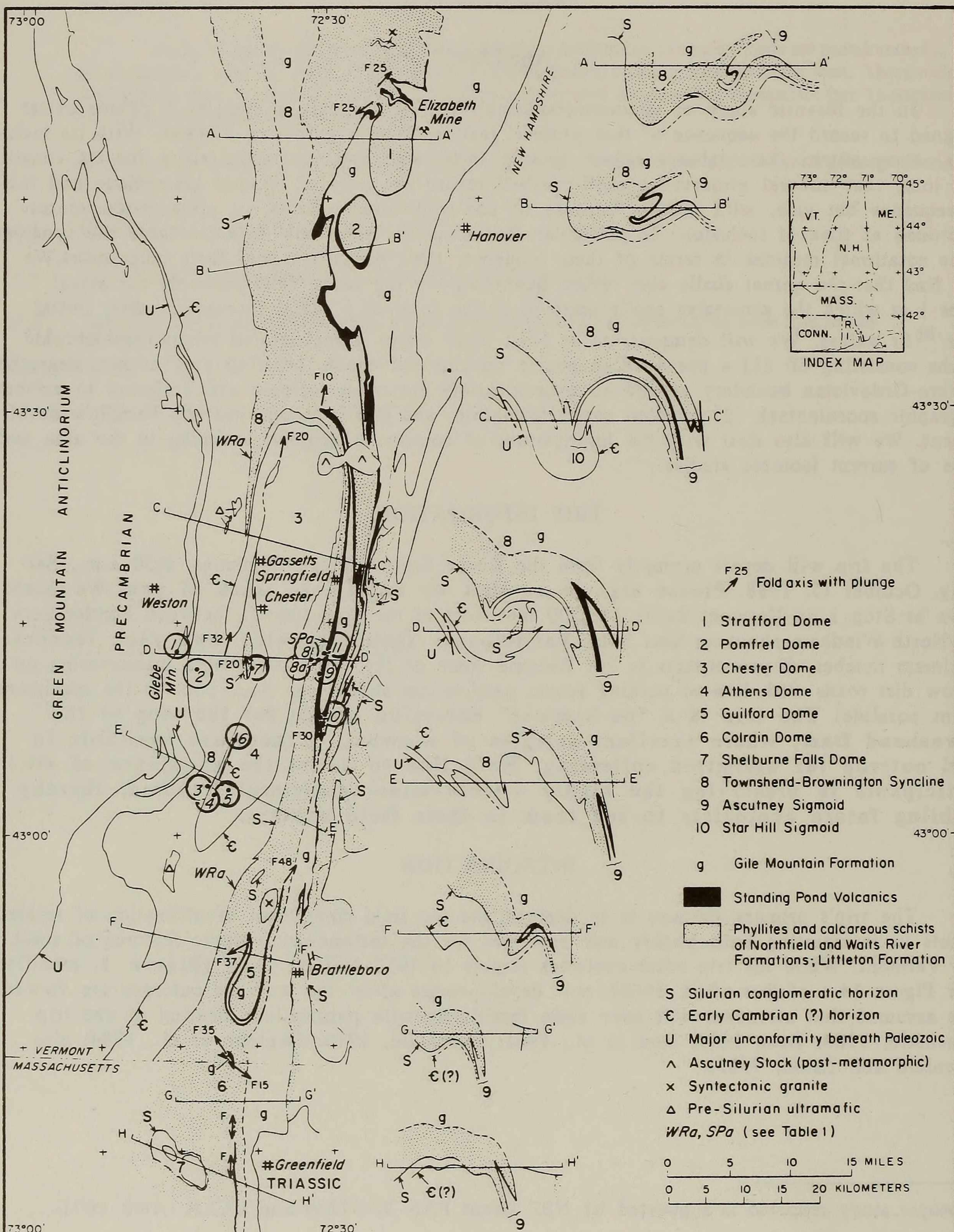


Fig. 1 - Field trip stops italicized. ◯

USE OF RUBIDIUM-STRONTIUM SYSTEMATICS IN DETERMINATION OF GROWTH-RATE

Among the new developments in particular, requiring a little elaboration, is our developing capability, using Sr-Rb systematics, to measure the growth-rate of large garnets and probably the times at which they grew. Besides the ability to measure isotopic ratios sufficiently accurately, the conceptual model itself appears to be in rather close accord with strict demands of Nature, namely that

1) garnet formed as an accreting, rigid, equant mineral, that crystallochemically excluded all but a trace of Rb and subsequently suffered no significant diffusion of Sr or Rb at the temperatures of concern.

2) garnet grew within a micaceous reservoir matrix that, in turn, sequestered and concentrated a sufficiently measurable amount of the trace element, Rb, within the large alkali positions of the micas, muscovite and biotite.

3) the matrix reservoir near garnet behaved as a closed system with respect to exchange of Rb and Sr with the environment outside the reservoir.

4) *except* for changes due to radioactive decay of ^{87}Rb, the matrix behaved like a well-stirred isotopically chemostatic bath for the relevant isotopes, Rb and Sr, during garnet growth.

One of the isotopes of Rb, ^{87}Rb, decays radioactively to ^{87}Sr. There is also always present a non-radiogenic reference isotope, ^{86}Sr, which, for the assumed model, stays constant within the system, garnet plus reservoir. Thus the growing garnet, which is chemically unable measurably to distinguish between ^{87}Sr and ^{86}Sr (unlike the case for lighter isotopes), acquires at its growth surface a trace amount of Sr having ^{87}Sr/ ^{86}Sr equal to that of the reservoir. Thus that ratio today is a function largely of distance from the center of nucleation, the measurable ^{87}Rb/ ^{86}Sr in the reservoir at the present, and time. Also d(^{87}Sr/ ^{86}Sr)/dt = (decay constant)*(^{87}Rb/ ^{86}Sr) $\approx$ a constant for a given specimen because of the very slow decay of ^{87}Rb. Thus, for all practical purposes, ^{87}Sr/^{86}Sr evolves as a straight-line function of time during garnet growth. Because two-point isochrons for garnet and matrix so far seem to give pretty good Acadian ages around 390 million years for the one outcrop so far studied in considerable detail, we may have a fairly good tool for dating metamorphic stages involving garnet growth during the prograde phase of metamorphism. We intend to test this possibility thoroughly.

GENERAL GEOLOGY

Stops will be in the old 15 minute Saxtons River Quadrangle (now available at 1:25,000 as the 7.5'x15' Saxtons River and Townshend Quadrangles) and are indicated on the summary geologic map and structure sections for southeast Vermont, **Figure 1**. **Figure 2**, a geologic map generated as an intermediate step in preparation of his part of G.S.A. Transect E-1 by J.B. Thompson, Jr. (by permission), provides a closer and more nearly up-to-date view of the geology. **Table 1** is the stratigraphic column, adapted and modified from Figure 2-1 of Hepburn et al. (1984). A principal contrast between **Table 1** and Figure 2-1 is the correlation of the Northfield Formation with the Gile Mountain Formation based on the finding by Rosenfeld, about 1,000 feet west of the Saxtons River - Westminster West Road west of Hartley Hill, of a thin discontinuous zone of Standing Pond Volcanic "look-alike" that he tentatively correlates with that unit. Also carried over in Figure 1 is the correlation of the Northfield Formation with the Littleton. That correlation no longer holds. Facing evidence along the contact between the Put-

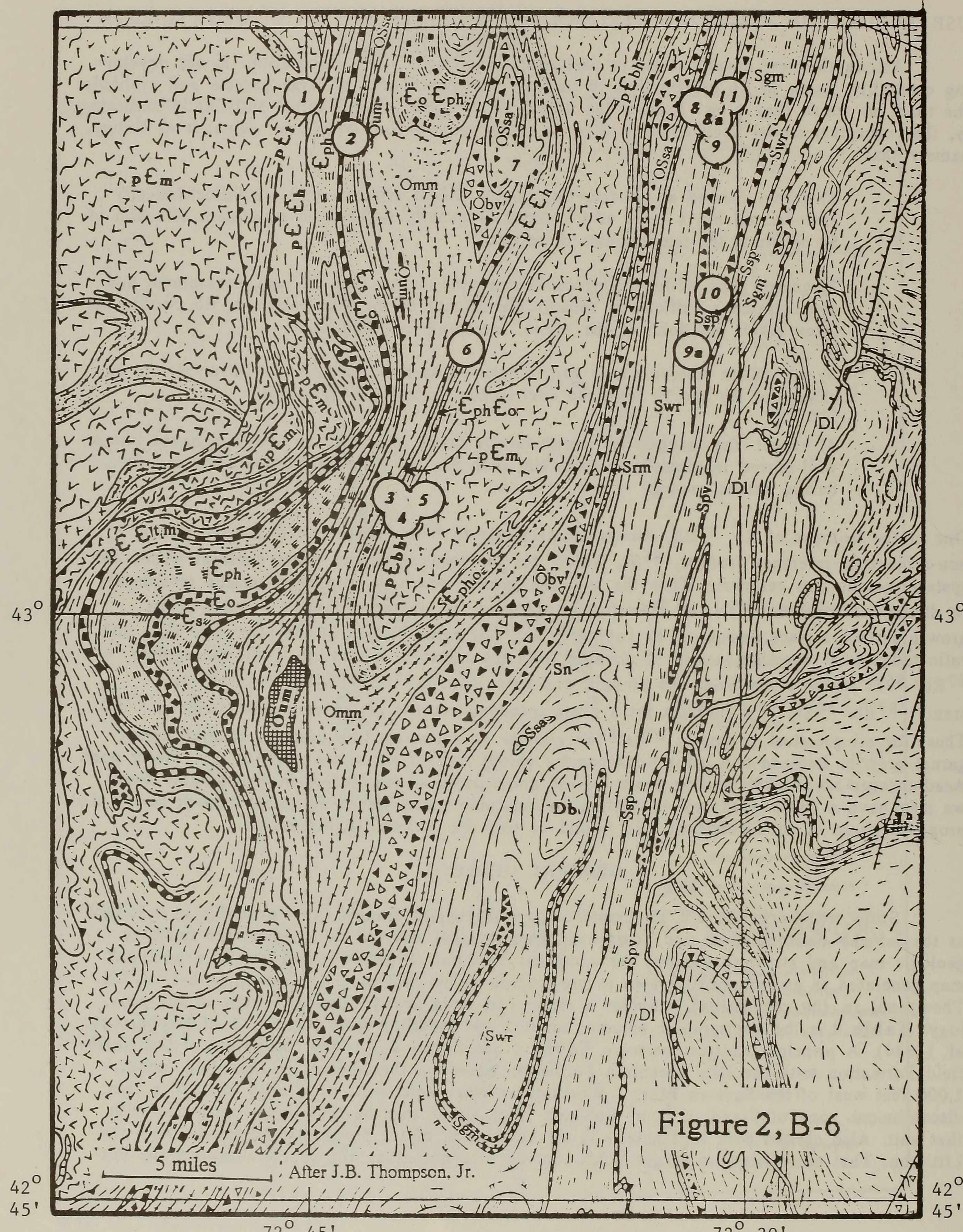

pЄm
pЄt
pЄh
pЄbh
pЄЄt,m
Єph
Єo
Єs
Єo Єph
Єph Єo
Єpho
Omm
Oum
Obv
OSsa
Sgm
Swr
Ssp
Spv
Srm
Sn
Db
Dl
5 miles
After J.B. Thompson, Jr.
43°
42° 45'
72° 45'
72° 30'

Figure 2, B-6

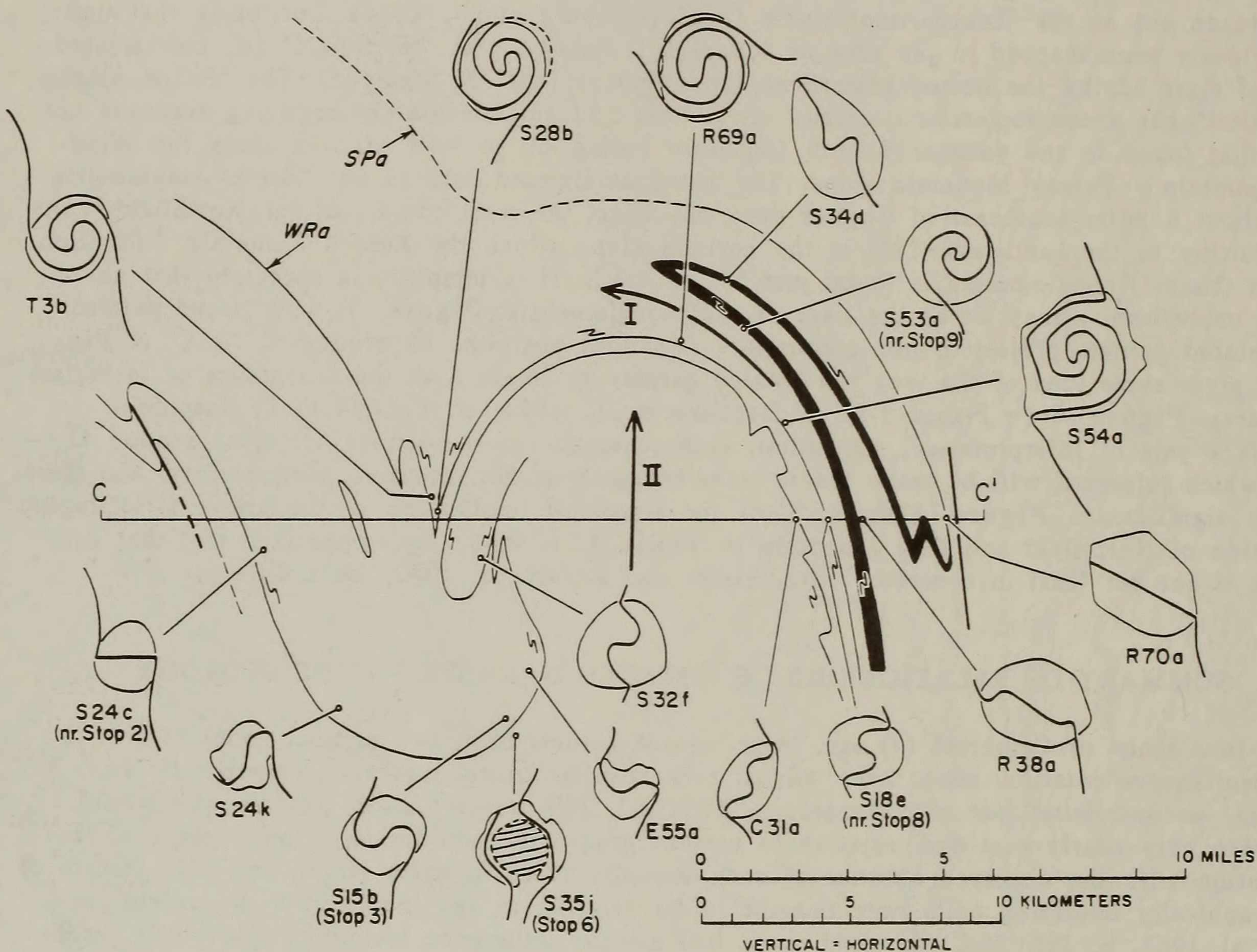
ney Volcanics, previously correlated in Figure 1 with the Standing Pond Volcanics, indicates that the Littleton is younger than the Putney Volcanics. The Putney Volcanics are probably much younger than the Standing Pond Volcanics. Also in the last few years, an important new unit has been broken out as the "Schist-Amphibolite Unit" (Hepburn et al., 1984). Previously that unit had variously been mapped in the area as "Cram Hill Schist," also "Northfield" (cf. the isolated synclinal mass having the dotted pattern on cross section D-D' of Figure 1). The "Schist-Amphibolite Unit" has a conglomeratic quartzite at its base and an immediately overlying sequence not unlike that found in the younger Russell Mountain Formation so well exposed along the Windmill Mountain - Putney Mountain ridge. The isoclinal sigmoid fold in the "Schist-Amphibolite Unit" about 6 miles southeast of Chester does not affect the west contact of the Northfield-Waits River further to the southeast. This is the horizon along which the Russell Mountain Formation with its (basal?) conglomerate is found just to the south. It is tempting to speculate that an important unconformity may lie at the base of that conglomerate. **Figure 3**, with traced patterns from rotated garnets projected into appropriate structural positions on section **C — C'** of **Figure 1**, gives some idea of the way the rotated garnets associate with the kinematics of tectonism in the area. **Figure 4** (= Figure 3-22 of Hepburn et al., 1984; cf. Fig. 14-11 in Rosenfeld, 1968) is a pair of interpretative, sequential, semi-schematic cross sections for cross section **C — C'** to which reference will be made below in referring to garnet rotations, their history, and their tectonic significance. **Figure 4** incorporates the structural implication of the above stratigraphic correlation of Northfield and Gile Mountain in **Table 1**. It should be emphasized that that correlation is not yet "cast in concrete!" (cf. Fisher and Karabinos, 1980, for a different viewpoint).

SUMMARY OF RELATIONSHIP OF ROTATED GARNETS TO THE GEOLOGY

In a schist of Cambrian (?) age, large rotated garnets have two distinct zones of growth and simultaneous rotation *about axes almost perpendicular to one another, separated by an "angular unconformity"* (see also Karabinos, 1984a,b). The restored early tectonic axis would have been very nearly east-west relative to present geographic coordinates. Combination of that information with the observed absence of such unconformities in much larger snowball garnets of stratigraphically overlying units now thought to be Silurian in age indicated to Rosenfeld (in Zen et al.,1968, p. 196) that the older rocks had already undergone tectonometamorphism, probably in the Ordovician Taconic Orogeny, before the younger Silurian rocks were deposited and subsequently subjected to a new tectonometamorphism during the Devonian Acadian Orogeny. Recent measurements by Christensen of core-matrix two-point Rb-Sr isochrons now indicate that the snowball cores may have crystallized as early as the Cambro-Ordovician boundary in a tectonometamorphic event that may have preceded the Taconic Orogeny. Although less precise, the $^{39}Ar/^{40}Ar$ laser mass spectrometry of Irwin et al. (1987) on a garnet from the same specimen reinforces the same interpretation. In particular both sets of isotopic measurements reinforce the interpretation that there were **two** tectonometamorphic events recorded by the unconformity garnets. Combined with the above discordance of rotational axes, these data do not accord with the conjecture of A.B. Thompson et al. (1977, p. 1163-1164) that the unconformities could have resulted from "one prograde process" in the Acadian.

Examination of the relict included surfaces in garnets of the younger Silurian rocks showed that the garnets commonly had two relict axes of rotation *not separated by growth unconformities* (Rosenfeld, 1970). The inner, or earlier, axes, characteristic of Acadian diastrophic event I, are rotated out of the schistosity in Acadian diastrophic event II by motion about outer, or later, axes within schistosity that are commonly at high angles to the earlier axes. Further, the earlier axes, after graphical correction for rotation about the later axes, are coaxial and cogenetic with large-scale, west-displaced nappes observable in the Silurian units that formed during event I before their arching and folding during development of both the Green Mountain Anticlinorium and structurally lower elongate mantled gneiss domes to the east during event II.

Figure 3, B-6



SPa
S28b
R69a
S34d
WRa
T3b
S53a
(nr. Stop9)
I
S54a
II
C
C'
R70a
S24c
(nr. Stop 2)
S32f
S24k
R38a
S18e
(nr. Stop8)
E55a
C31a
S15b
(Stop 3)
S35j
(Stop 6)
0
5
10 MILES
0
5
10 KILOMETERS
VERTICAL = HORIZONTAL

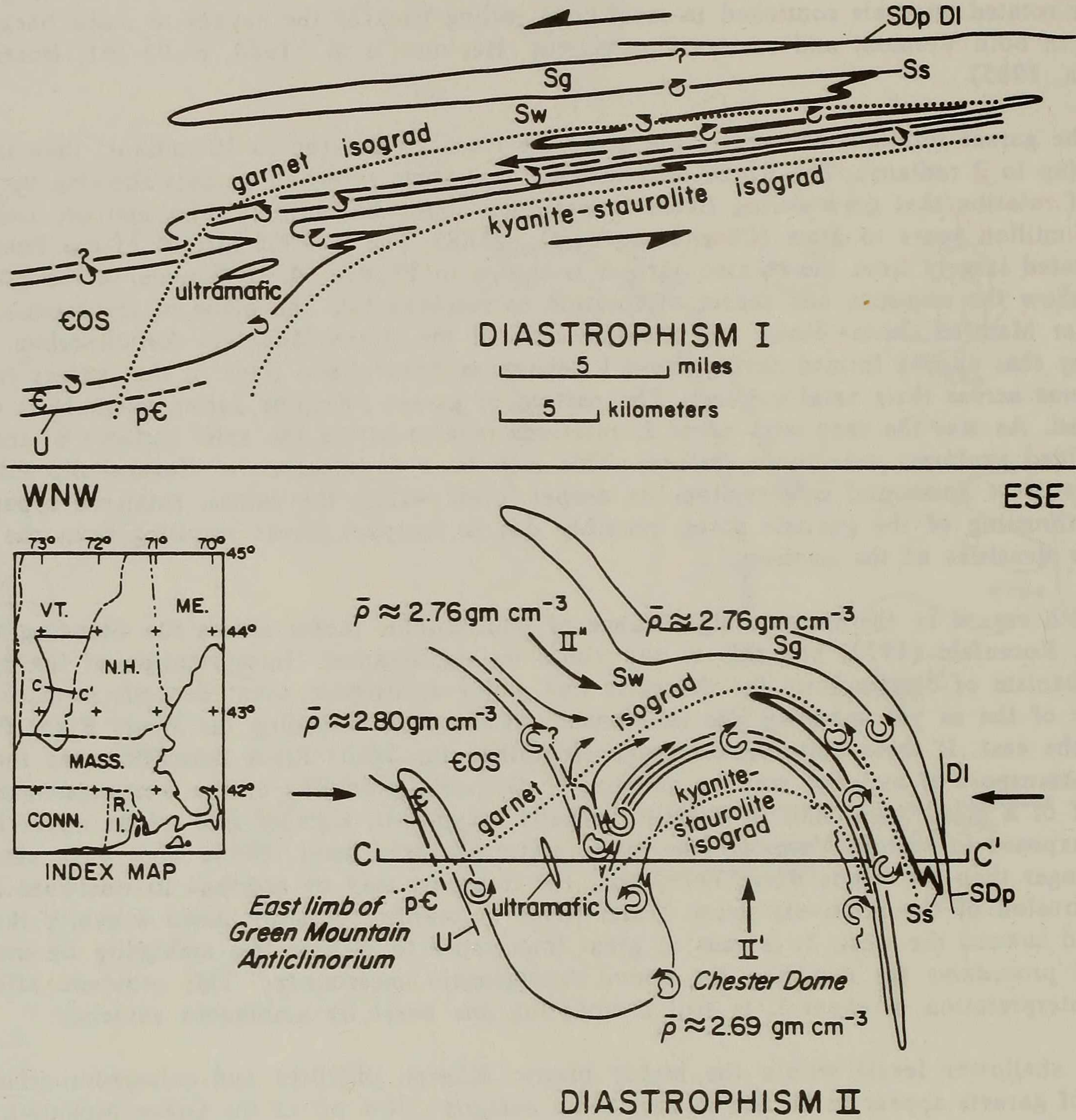
Viewed in a northerly direction (**the convention used unless otherwise stated**), snowball garnets in the lower Waits River Formation on the Chester and Athens Domes rotated in a counter-clockwise direction during event I. Those along the west side of the Standing Pond Volcanics on the west limb of the Ascutney Sigmoid rotated clockwise. Late in event II the garnets and other rotated minerals continued to record the rolling back of the nappes to make backfolds, observed in both Vermont and eastern Connecticut (Hepburn et al., 1984, p. 93-101; Rosenfeld and Eaton, 1985).

The garnet rotations of event I are generally much greater (up to 10 radians) than those of event II (up to 2 radians). The Rb-Sr data indicate that some snowball garnets showing up to 4 radians of rotation that grew during Event I developed about 390 million years ago and took about 10 million years to grow (Christensen et al., 1988). The tectonic history of the two events as interpreted largely from the rotated garnets is shown in **Figure 4**. In **Figure 4** the rotation symbols show the sequence and senses of rotation as resolved into the plane of the section across the Chester Mantled Gneiss Dome and the east limb of the Green Mountain Anticlinorium. It is noteworthy that nappes formed during event I behave as flexural-slip folds in that garnet rotations reverse across their axial surfaces. The pattern of garnet rotations during event II is more complicated. As was the case with event I, rotations reverse across the axial surfaces of the tightly folded synforms near those surfaces. This may be a consequence of flexural-slip folding due to east-west horizontal compression. At deeper levels within the domes, rotations appear to reflect upthrusting of the gneissic cores, possibly due to buoyant forces resulting from the relatively low densities of the gneisses.

With regard to the tectonic significance of stratigraphic facing across the Standing Pond Volcanics, Rosenfeld (1972) had this to say about its significance: "Interpretation of the proximate mechanism of diastrophism for the early and major diastrophic event depends primarily upon knowledge of the as yet unknown age relationship of the units bounding the Waits River Formation on the east. If these units should prove older than the Waits River Formation, the indicated westward transport of material may be ascribed to flexure-slip folding of the westward-opening lower half of a giant lower half of a giant, initially recumbent, sigmoid fold whose upper half is nowhere exposed in eastern Vermont [the interpretation favored here]. If the same units should prove younger than the Waits River Formation, the transport may be ascribed to westward intrastratal extrusion of the relatively dense Waits River Formation, possibly down a gently inclined slope tilted toward the west. It is thus of great importance to resolve this ambiguity by development of procedures for resolving the above stratigraphic uncertainty." This problem, affecting tectonic interpretation of event I, is still a troubling one beset by ambiguous evidence.

At shallower levels within the highly plastic Silurian phyllites and calcareous schists, rotations of garnets appear to be due in part to an *easterly* flow off of the Green Mountain anticlinorium and over the Chester and Athens mantled gneiss domes, shown by streamlines in **Figure 4**. This is in the opposite direction of the earlier *westerly* transport of the nappes that were bowed up by those domes. This signifies that tectonism at a scale even larger than that of the geologically mapped large structures was involved. At that time before the plate tectonic hypothesis (1959), the picture was not very clear as to just what that larger scale process was, although Rosenfeld recalls thinking that it might well have been related to an asymmetric "Benioff-type" gravity pattern then recently observed in the area and associated with thrust faults by R.J. Bean (1953). Bean's interpretation was consistent with the clearly higher structural level of the Green Mountain Anticlinorium relative to the Chester, Athens, and Guilford Domes to the east. At the time of writing of the original study (Rosenfeld, 1968), the possible plate tectonic implications of *retrocharriage* had not yet sunk in. This large-scale flow, extending across the major structures of event II, is like that which must have caused the well-known back-folds in the central Alps, described long ago by Argand. It caused some backfolding in southeast Vermont

Figure 4, B-6



EXPLANATION

DI gray schist
SDp greenschists (volcanic)
Sw calcareous schists and phyllites
Ss greenschists and amphibolites (volcanic)
Sg quartzo-feldspathic schist, phyllite, calcareous schist

€OS schists, gneisses, amphibolites
€ augen gneiss, albitic and paragonitic schist, dolomite
U major unconformity
p€ polymetamorphic gneisses, schists, amphibolites, marbles

(Hepburn et al., 1984, p. 93-101). The backflow or *retrocharriage* would seem to have resulted from eastward tilting of the lithospheric substrate underlying the anticlinorium and the dome, perhaps a consequence of major and deep westward overthrusting affecting the lithosphere underneath and to the west during event II (cf. Ando et al., ☞∞, 1984). Acadian *retrocharriage* also displays itself well in eastern Connecticut (Rosenfeld and Eaton, 1985). As of the time of writing we have not obtained Rb-Sr evidence as to the timing of event II.

REFERENCES

Ando, C.J., Czuchra, B.L., Klemperer, S.L., Brown, L.D., Cheadle, M.J., Cook, F.A., Oliver, J.E., Kaufman, S., Walsh, T., Thompson, J.B., Jr., Lyons, J.B., and Rosenfeld, J.L., 1984, Crustal Profile of a Mountain Belt: COCORP Deep Seismic Reflection Profiling in New England Appalachians and Implications for Architecture of Convergent Mountain Chains, Bulletin, American Association of Petroleum Geologists, 68, p. 819 - 837. (research paper).

Bean, R. J., 1953, Relation of gravity anomalies to the geology of central Vermont and New Hampshire: Geol. Soc. America Bull., v. 64, p. 509-538.

Christensen, J.N., Rosenfeld, J.L., and DePaolo, D.J., 1988, Rates of tectonometamorphic processes: direct measurement using Sr isotopic profiles of garnet porphyroblasts, EOS, v. 69, p. 508.

Doll, C. G., Cady, W. M., Thompson, J. B., Jr., and Billings, M. P., compilers and editors, 1961, Centennial geologic map of Vermont: Montpelier, Vermont. Vermont Geol. Survey, scale 1:250,000.

Fisher, G.W., and Karabinos, Paul, 1980, Stratigraphic sequence of the Gile Mountain and Waits River Formations near Royalton, Vermont, Geological Society of America Bulletin, Part 1, v. 91, p. 282-286.

Hepburn, J.C., Trask, N.J., Rosenfeld, J.L., and Thompson, J.B.,Jr., 1984, Bedrock geology of the Brattleboro Quadrangle, Vermont-New Hampshire, Vermont Geol. Survey Bull. 32, Agency of Environmental Conservation, Dept. of Water Resources and Environmental Engineering, Montpelier, Vermont, 162 p. (with colored geologic map and cross sections).

Irwin, J.J., Kirschbaum, C., Rosenfeld, J.L., and Glassely, W.E., 1987, An argon isotope study of an "unconformity garnet" from southern Vermont using a laser micropobe, EOS, v. 68, p. 1514.

Karabinos, Paul, 1984a, Deformation and metamorphism on the east side of the Green Mountain massif in southern Vermont: Geol. Soc. Amer. Bull., v. 95, p. 584-593.

__________, 1984b, Polymetamorphic garnet zoning from southeastern Vermont, Amer. Jour. Science, v. 284, p. 1008-1025.

Laird, J., and Albee, A.L., 1981, Pressure, temperature, and time indicators in mafic schist: their application to reconstructing the polymetamorphic history of Vermont, Amer. Jour. Science, v. 281, p. 127-175.

Laird, J., Lanphere, M.A., and Albee, A.L., 1984, Distribution of Ordovician and Devonian Metamorphism in mafic and pelitic schists from northern Vermont, Amer. Jour. Science,

v. 284, p. 376-413.

Rosenfeld, John L., 1954, Geology of the southern part of the Chester Dome, Vermont, Ph.D. Dissertation, Harvard University, 303 p.

__________, 1970, Rotated Garnets in Metamorphic Rocks, Geol. Soc. Amer., Spec. Paper 129, 105 p.

__________, 1972, Rotated Garnets and Tectonism in Southeast Vermont, Trip 7, in Guidebook for Field Trips in Vermont, 64th Ann. Mtg., New England Intercollegiate Geol. Conf. 1972 [Burlington, Vermont: Dept. Geol., Univ. Vermont] p. 167-178.

__________, 1987, Rotated Garnets, p. 702-709 in Encyclopedia of Structural Geology and Plate Tectonics, C.K.Seyfert, Editor, Volume X of Encyclopedia of Earth Sciences Series, R.W. Fairbridge, Series Editor, New York, Van Nostrand - Reinhold, 876 p.

__________, "Schistosity," in Preferred Orientation in Deformed Metals and Rocks: An Introduction to Modern Texture Analysis, H.-R. Wenk, Editor: Academic Press, Inc., Orlando, p. 441 - 461.

__________, and Eaton, G.P., 1985, Geology of the Middle Haddam Area, Revisited, in Guidebook for Field Trips in Connecticut and Adjacent Areas of New York and Rhode Island: 77th Annual Meeting of the New England Intercollegiate Geological Conference, October 4, 5, and 6, 1985, published as Trip B5, Guidebook No. 6, State Geological and Natural History Survey of Connecticut, Natural Resources Center, Department of Environmental Protection, Hartford, Connecticut, p. 297 - 321 + abstract (insert) + 5 p. road log (insert).

Thompson, A.B., Tracy, R.J., Lyttle, P.T., and Thompson, J.B.,Jr, 1977, Prograde reaction histories deduced from compositional zonation and mineral inclusions in garnet from Gassetts Schist, Vermont, Amer. Jour. Science, v. 277, p. 1152-1167.

TABLE 1, TRIP B-6

Lithologic Units

Stratigraphic units:

Dl	Littleton Formation. Monotonous grey slate and schist with thin conglomerate at its contact with the Putney Volcanics.
	——Major unconformity?——
Spv:	Putney Volcanics. Buff to light brownish-gray feldspathic phyllite; thin beds of feldspathic granofels; light greenish-gray phyllite; minor gray slate.
Swr:	Dark gray mica schist and calcareous mica schist with abundant interbeds of punky-brown-weathering, impure marble; thin interbeds of impure quartzite.
Ssp:	Standing Pond Volcanics. Dark gray to black, medium-grained amphibolite and epidote amphibolite predominant; very coarse grained garnet-hornblende fasciculite

schist; rare, impure quartzite, coticule and schist (western bands). Gray to greenish, massive plagioclase-biotite-quartz and plagioclase-biotite-hornblende-quartz granofels (eastern band).

Sgm, Sn: Gile Mountain and Northfield Formations. Interbedded light gray, impure quartzites and mica schist. Gray, fine-grained phyllite and slate with interbedded, thin, micaceous quartzite and subordinate, punky - brown-weathering impure marble (eastern band). Some interbedded black phyllite.

Srm: Russell Mountain Formation. Light gray to white quartz pebble conglomerate and quartzite at and near base; coarse-grained hornblende fasciculite schist; medium-grained amphibolite; silvery schist with tiny euhedral garnets and containing abundant nodules composed of manganiferous garnet, quartz, and apatite

——————————————Major unconformity?——————————————

OSsa: Schist-Amphibolite Unit. Basal conglomeratic quartzite; rusty-weathering black carbonaceous phyllite and schist; minor gray schist, black amphibolite, black platy quartzite, thin-laminar magnetite-cummingtonite coticule beds common, blasto-porphyritic amphibolite common.There is a distinctive sequence at the base of this unit northwest of Grafton: conglomeratic quartzite; overlain in turn by amphibolite; silvery schist with tiny euhedral garnets and containing abundant nodules composed of manganiferous garnet, quartz, and apatite; thin, buff-white micaceous calcite marble; garnetiferous graphitic schist.

——————————————Unconformity?——————————————

Obv: Missisquoi Formation, Barnard Volcanic Member. Dark gray to black, poorly to well-foliated amphibolite and porphyritic amphibolite; gray to light gray quartzo-feldspathic gneiss, schist, granofels and layered gneiss; minor black, rusty-weathering mica schist, especially at top northwest of Grafton.

Omm: Missisquoi Formation, Moretown Member. Gray to light gray, interbedded quartzite, quartz-mica schist, and impure quartzite. Distinctive laminated "pinstriped" quartzite locally abundant; 10-20% medium-grained amphibolite and garnet amphibolite.

Ꞓs Stowe Formation. Garnetiferous chlorite-sercite schist with abundant quartz lenses; subordinate greenish to black amphibolites. Separately mappable only on the east limb of the Green Mountain Anticlinorium

Ꞓo: Ottauquechee Formation. Dark gray, rusty-weathering pyrrhotitic mica schist, commonly graphitic, notable for large garnet porphyroblasts; epidote amphibolite; gray to black quartzite interbeds; highly paragonitic near base.

Ꞓph: Pinney Hollow Formation. Light green quartz-muscovite-chlorite schist with quartz lenses, commonly paragonitic with thin interbedded laminar epidote amphibolites, especially abundant near top of unit, where they are sometime separately mapped as "Chester Amphibolite." In some places has garnets up to an inch in diameter containing growth "unconformities." Schist occasionally has thin pale pink coticule lenses.

pꞒ-Ꞓh: Hoosac Formation. Mica schist with conspicuous albite porphyroblasts and flaggy well-banded gneisses; epidote amphibolite, some with large epidote nodules (where separately mapped is called Turkey Mountain Amphibolite = **pꞒ-Ꞓtm**); silvery paragonitic garnet-muscovite schist with staurolite porphyroblasts and containing garnets up to 1 inch in diameter in some places.

---

p€t Tyson Formation. Discontinuous polymict conglomerate gneiss at base in some places associated with overlying dolomitic marble; feldspathic muscovite schist.

————————————Major unconformity————————————

p€bh: Bull Hill Gneiss. Microcline augen gneiss.

————————————Major unconformity?————————————

p€m: Mount Holly Gneiss. Heterogeneous gneisses, commonly quartz-biotite-plagioclase gneiss; some coarse marbles associated with calc-silicates, commonly rusty weathering due to pyrrhotite and containing coarse crystals of graphite.

Non-stratified rocks:

Db Black Mountain Granite. Biotite-muscovite microcline syntectonic granite.

Oum Ultramafics occasionally preserving their protolithic character in the form of olivine and pyroxene, but more often altered to serpentine containing abundant carbonate and magnetite in the lower metamorphic grades and soapstone containing talc, carbonates, and various strange biopyroboles in the higher grades.

ITINERARY

Road log begins on Route 11, just west of the summit of the pass over the east range of the Green Mountains, 0.5 miles southwest of North Windham, Vermont, about 200 feet west of the west boundary of the Saxtons River Quadrangle.

Mileage

0.0 STOP 1. Angular unconformity between a sliver of the overlying prograde metamorphosed basal conglomerate of the Tyson Formation and the underlying retrograde metamorphic rocks and pegmatites of the Precambrian Mount Holly complex. This unconformity is significant for this trip because it demonstrates the direction of stratigraphic "tops." Proceed easterly on Route 11 through the Hoosac Formation. This unconformity was originally noted and mapped by T. Nelson Dale near the beginning of this century (unpublished U.S.G.S. manuscript map). The polymict basal conglomerate is much more convincing at Dry Hill to the north west of Lake Amherst and to the south on the west side of Glebe (Magic) Mountain.

0.6 North Windham. Turn right onto Rte. 121.

0.8 Northernmost exposures of Turkey Mountain Member (amphibolite) of Hoosac Formation outcrop as a sliver only a few feet thick in draw to west. Continue through schists of Pinney Hollow Formation.

2.2 Near crest are exposures of Chester Amphibolite Member of Pinney Hollow Formation. Strong down-dip lineation of pale green amphiboles. Nearby some have been observed by Laird and Albee (1981) to have actinolite cores. Continue through Ottauquechee and Stowe Formations.

2.6 STOP 2 at Lawrence Four Corners. First rotated garnet locality in outcrop at northwest corner of intersection. Garnets in schist of Stowe Formation show small counterclockwise rotation after growth about nearly horizontal axes when viewed in a northerly direction (the direction of view used subsequently unless otherwise stated). Note effect of garnet rotation on bending of adjacent schistosity. Proceed southerly from Rte. 121 on Windham Road past outcrops of Stowe Formation and rusty schists of the Ottauquechee Formation.

4.0 Windham Center. From here almost to South Windham, the road lies within the banded rusty-weathering graphitic schists of the Ottauquechee Formation. Rise in metamorphic grade is most evident in the field in the transition from pale green amphibolites to dark green to black amphibolites. At the stone bridge at the bottom of the hill immediately south of Windham Center we cross the oligoclase isograd (originally mapped by Rosenfeld, 1954), northwest of which plagioclase more calcic than nearly pure albite is not found, regardless of bulk composition of the rock. Coexisting oligoclase and albite, first observed here using optical immersion methods, can be found in amphibolites just upstream from the bridge. The oligoclase isograd is related to a miscibility gap within the plagioclase feldspar series.

You may be interested in an historical note about the above stone bridge that gives some insight into Vermont, Vermonters, and how times have changed. One day back in the late '40s, an old-timer by the name of Reilly happened to look down from the bridge upon Thompson and Rosenfeld deeply engrossed in the brook outcrop. With an "I gotcha" smile not unknown in these parts, he inquired of those "city-slickers" if they reckoned how much it had cost to build the bridge. Thompson, perhaps harking back to his childhood days among similar folk "down-east" in Maine, paused and then threw out the figure, $50.00. This wiped the smile off Mr. Reilly's face. Somewhat subdued — crest-fallen might be a more apt description — he averred as how he had built that bridge, and that's exactly what it cost! Hence this bridge will ever be known as Reilly's "Fifty-Dollar Bridge!"

7.6 South Windham. Chester amphibolite. In this unit on the ridge just to the northwest, Laird, Lanphere, and Albee (1984, p.387) have obtained an $^{40}Ar/^{39}Ar$ age on amphibole of 376±5.0 million years.

8.0 Jamaica-Townshend town line. Enter the typical green garnet-magnetite-chlorite-sericite schist comprising the main part of the Pinney Hollow Formation and through which the road passes for the next 2.0 miles.

10.0 Turkey Mountain Member appears on ridge to west. From here to West Townshend we pass down-section from the Pinney Hollow Formation into the characteristic albite schists of the Hoosac Formation. To the west of here large isoclinal folds are involved in major thrust faults toward the west (Karabinos, 1984; also Rosenfeld, 1954, geologic map) that probably connect with the fault offsetting the unconformity at the base of the Tyson Formation near STOP 1 that was inferred by Rosenfeld (1954; cf. Figure 2). Not showing on Figure 2 is the extension of the Turkey Mountain Member, traced by Rosenfeld, along Glebe (Magic) Mountain Ridge almost to North Windham; that member is well exposed at the top of the main ski lift at Magic Mountain. A short apparent gap in this unit near Cobb Brook Falls is probably explained by the above-mentioned fault. This fault and others like it may be related to the *retrocharriage* discussed in the text.

11.6 Roadcuts on west side of highway show eastward dipping beds of "pinstripe" in Moretown with a prominent boudinage fracture having horizontal orientation. Continue in highly contorted schists and amphibolites of the Moretown across the axis of the Townshend-Brownington syncline onto the west limb of the Athens (pronounced Aythens) dome.

12.8 Thin amphibolites in smooth coutcrops of Moretown on the left exhibit boudinage.

13.1 Park cars in parking area on right at Townshend Flood Control Dam. STOP 3 is in the roadcut on the northeast side of the highway opposite the dam. The cut is an almost complete exposure of the Ottauquechee Formation, the best and most nearly complete exposure of that unit on either the Chester or Athens Dome. Snowball garnets show counterclockwise rotation on the west limb of the Athens dome. Note the relative consistency of the shear sense indicated by the rotated garnets in contrast to that of the drag folds. The origin of this contrast has been discussed elsewhere (Rosenfeld, 1970, p. 92). Also note the large boudinage fractures in amphibolites here.Garnets observed here are believed to have grown and rotated before development of the Athens dome during Acadian Event I. The relict "oligoclase isograd" may be observed in the form of coexistent albite, oligoclase, and clinozoisite encapsulated in garnets at this locality (Rosenfeld, 1970, p. 90-91), even though the staurolite isograd is only a short distance east. This would seem to be good evidence of growth of the garnets over a considerable range of temperatures. The lowest part of the Ottauquechee Formation, exposed just to the north of the highway about a couple of hundred feet southwest of the dam, is a rusty-weathering paragonite schist having large garnets up to 3cm in diameter. Some of these are the first to have had their growth duration measured. They took about 8 million years to grow as determined from the decay, $^{87}Rb \rightarrow {}^{87}Sr$. Precision is about 2.5 million years. One of these, having the characteristic snowball pattern with rotation of almost 4 radians, thus gives some idea of strain-rate during prograde metamorphism, here about $3 \times 10^{-14} sec^{-1}$. Proceed southeasterly on Rte. 30 through Pinney Hollow Formation amphibolites and schists to the Hoosac Formation.

13.5 Scott covered Bridge on right. Amphibolite in what is believed to be Hoosac Formation on left. If these rocks correlate with the main band of the Hoosac to the west, they are of a distinctly more banded and gneissic facies. Just beyond the bridge on the left are some very nice secondary drag folds on a large fold, incompletely exposed in the outcrop.

13.8 STOP 4. Conglomerate gneiss of Tyson Formation (?) on west in contact with Bull Hill Gneiss, which maps out as a stratigraphic unit on the Chester and Athens Domes. Paul Karabinos and John Aleinikoff have currently been doing U-Pb lead determinations on zircon grains in this unit, getting post-Grenville ages between 900 million and a billion years. Because of the Bull Hill gneiss' granitic composition and its stratigraphic character, it is possible that that unit represents a metamorphosed stack of rhyolitic volcanics. In the southern part of the Athens dome, it has not been possible to delineate accurately the boundary between the Bull Hill gneiss and what are believed to be older but lithologically similar Precambrian granitic augen and flaser gneisses in the core of the dome. Note counterclockwise drag folds in gneiss, believed to be a result of upthrusting of the gneissic core of the dome. Proceed easterly on Rte. 30 through broad zone of granitic gneisses to

15.0 Townshend. Turn left off Rte. 30 onto Rte. 35 and proceed northerly.

15.4 STOP 5. Outcrops lie across the field to the west and consist of magnetite-bearing granite flaser gneiss, believed to have been representative of the relatively low-density "plunger" accounting for the buoyant upward thrust of the Athens dome. Continue north on Rte. 35 through heterogeneous gneisses, some rusty weathering and containing coarse graphite flakes rather like the Washington gneiss described by Emerson in the Berkshires.

16.9 Simpsonville.

18.4 Easy to miss intersection. Bear left off Rte. 35 onto Grafton Road.

18.6 For the next 0.2 miles, passing through a band of calc-silicate rocks, characterized by coarse graphite flakes and pyrrhotite, that strikes northeasterly through the core gneisses of the Athens dome at a large angle to the mantling strata. This discordance provides, perhaps, the best evidence to date that the core gneisses of the Athens dome lie unconformably beneath the mantling strata.

18.8 Continue through banded, contorted, biotite gneisses of the core of the Athens dome.

19.6 Top of grade. Bull Hill Gneiss on dip slopes along east side of South Branch of Saxtons River to north. Valley probably owes its alignment to an easily eroded dolomite (observable at a number of localities on Rte. 35 north of Grafton) that separates albite schist of the Hoosac Formation on the west from the Bull Hill Gneiss.

20.3 Easy to miss turn. Turn sharply left onto single lane, steep dirt road (Acton Hill Road). Proceed through Hoosac Formation.

20.6 Cross brook.

20.9 East contact of garnet-kyanite-straurolite-paragonite schist of Pinney Hollow Formation in core of anticlinal portion of Ober Hill Fold. Pass across Ober Hill Fold.

21.6 Intersection. Let lead car turn around before entering intersection. Then, one by one, each car should turn left, then back up sufficiently far to make room for following cars to do same. Continue back down the Acton Hill Road, following lead car.

21.8 Park your car as far off the road to the right as possible. STOP 6, exhibiting garnets with angular growth unconformities (Rosenfeld, 1968, p. 196), is on the ledges visible to the southwest of the road west of a kyanite-rich paragonite schist. The rock is a garnet-staurolite-paragonite-muscovite schist. Chloritoid and staurolite exist as an armored relict assemblage inside the garnets here. There is no chloritoid outside the garnet. The earlier garnet, showing snowball character, may have grown at about the Cambro-Ordovician boundary possibly during a pre-Taconic tectonometamorphism (see text above). Proceed back toward Townshend-Grafton Road.

22.1. On the left are some remarkably fine counterclockwise drag folds, some of which have transcurrent "slip fractures" of similar shear sense about the same axis. These fractures provide evidence of the "lateness" of these folds.

22.9 Townshend-Grafton Road. Turn left and continue north.

27.7 Grafton, a picturesque village in which some of the finer examples of old Yankee architecture have been restored and preserved by the liberal application of dollars by the Windham Foundation. The local Cheddar cheese from the store we pass in the south part of the village is some of the best made in Vermont. Recently "Funny Farm," starring Chevy Chase, was shot here. You may spot some of the "local characters" that added authenticity to that film. Turn left onto Rte. 121, passing successively through a rather complete section of units from the Hoosac Formation to the rusty-weathering, graphitic schists atop the Barnard Volcanics, formerly correlated with the "Cram Hill Schist" of Jahns, that have not yet received a new name.

29.9 STOP 7. Westward dipping beds of conglomeratic quartzite and interbedded garnet-muscovite schist at base of Schist-Amphibolite Unit. These beds lie on the east limb of a syncline (Spring Hill Syncline) whose axial surface dips to the west. This syncline was previously believed to be the detached (by megaboudinage) westward-opening, lower part of the Star Hill sigmoid (Figure 1, Section D-D'). Now it is not at all clear how it fits into the multiple tectonism to which it has been subjected and constitutes a puzzle that Jim Thompson, Carl Jacobson of Iowa State, and Rosenfeld have been struggling with. Staurolite and kyanite occur in some of the schists contained within the syncline. The sequence of rotations found in snowball garnets within a schistose parting in the quartzite a mile to the north is: early clockwise, late counterclockwise. Turn around and return to

32.1 Grafton on Rte. 121, continuing through the village across the Saxtons River and turning left onto

32.2 Rte. 35, proceeding northerly along approximately the same stratigraphic horizon that was followed south of Grafton. Bull Hill Gneiss to east.

33.9 Dolomite under albite schist of Hoosac Formation on left. Leaving Athens Dome; entering Chester Dome.

36.4 Enter Grafton Gulf.

36.9 Leave Grafton, Windham County; enter Chester, Windsor County.

37.0 Note pillar of dolomite supporting albite schist on left, dip slope of Bull Hill Gneiss on right.

37.5 Summit of Grafton Gulf.

38.3 Leave Saxtons River Quadrangle; enter old Ludlow Quadrangle (new Chester Quadrangle).

39.5 Chester. Turn right onto Rte. 103.

40.9 Return to Saxtons River Quadrangle.

42.3 Bull Hill Gneiss on east limb of Chester Dome. One of localities dated by Paul Karabinos and John Aleinikoff.

42.5 Enter town of Rockingham, Windham County. Crossing Hoosac Formation.

42.7 Crossing from Pinney Hollow through intermediate units into Moretown Formation.

44.3 Easy to miss intersection. Turn sharp left off Rte. 103 onto dirt road with bridge over railroad tracks.

44.4 Car junkyard on left.

44.5 Covered bridge.

44.9 STOP 8. Ledges in woods north of road. Sieve texture garnets in calcareous schists of lower Waits River Formation showing early counterclockwise rotation (Event I; conspicuous) followed by late clockwise rotation (Event II; observed with difficulty). Continue easterly.

45.7 Optional STOP 8a. Main zone of calcareous schists with subordinate phyllites within Waits River Formation in what used to be one of the best exposures of the Waits River Formation in southern Vermont before recent construction of a power dam. Big sprays of zoisite. Isoclinal folding. Easily observed rotated garnets. Mafic dike with multiple chilled borders and euhedral calcite phenocrysts observable in the chilled borders in thin section. Turn right across bridge and railroad tracks.

46.0 Turn left onto Rte. 103.

46.2 Turn right off Rte. 103 onto Pleasant Valley Road. Passing through heterogeneous rock types of Standing Pond Formation, mostly mafic volcanics.

47.1 Turn right off the Pleasant Valley Road onto single lane dirt road.

47.2 Park cars and proceed northerly across field about 1,500 feet into woods just northwest of northwest corner of field to STOP 9 at contact between garnetiferous phyllite of Waits River Formation on west and coarse garnetiferous schist of the Standing Pond Formation containing sprays of hornblende (fasciculitic schist or "garbenschiefer"). Large garnets show only a single large clockwise rotation associated with Event I, in contrast to those at Stop 8. A photograph of a rotated garnet from this locality appears as figure 14-6 in Rosenfeld (1968, p. 195). Evidence of Event II at this locality appears only as gently northward plunging crinkles. For further discussion of this locality, see Rosenfeld, 1970, p. 89. Return to Pleasant Valley Road by car.

47.3 Turn right onto Pleasant Valley Road.

48.7 Septum of Waits River-like calcareous schist and phyllite in Standing Pond Formation.

48.8 Exposures of banded and massive amphibolites of Standing Pond Formation near eastern contact with Gile Mountain Formation. Clockwise drag folds. Road continues southerly along east side of Standing Pond Formation.

51.0 Intersection with Rte. 121. **Dangerous intersection**!!!! Continue east on Rte. 121.

51.3 Village of Saxtons River. Turn right and go south across bridge over Saxtons River following paved road for about a third of a mile past Kurn Hattin orphanage on left and continuing straight ahead at sharp bend onto Hartley Hill Road (dirt road) continuing up the hill on same.

52.6 About 0.36 miles beyond town line between Rockingham and Westminster just beyond curve to left, turn right onto poorer quality road.

53.0 Turn around and park. STOP 9a is about a hundred feet into the woods east of the road. The horizon of the Standing Pond Formation to be observed is slightly into the unit but otherwise on strike from the outcrop observed at STOP 9. It is not marked on Figure 1 but is just northeast of the "0" in "F30" on Figure 1. This is one of the best places to see in three dimensions the shapes of the included surfaces of the snowball garnets on a weathered steeply dipping dip surface. Here it is easy to see the orientations of rotational axes in the field. Rotational sense is clockwise. Return to

54.7 Saxtons River Village and park just north of bridge. STOP 10. The purpose of this stop is to observe southward plunging minor folds in the Standing Pond Formation along the axis of the upward closing fold (anticline) of the Ascutney Sigmoid. The axis of this horizon reappears to the south on the Guilford Dome near the syntectonic Black Mountain Granite in Dummerston (fig. 1). Folds with counter-rotating garnets on their limbs appear along the north side of the river, 0.3 miles to the west (Rosenfeld, 1970, p. 85-86). Turn westerly on Rte. 121. For a discussion of the relationship of the rotated garnet history here and at the same structural position on the Guilford Dome as affected by the Black Mountain Granite, see Hepburn et al. (1984).

55.0 Bear right off Rte. 121 onto Pleasant Valley Road.

59.6 Turn left off the Pleasant Valley Road onto Rte. 103.

59.8 Turn right off Rte. 103 toward Brockways Mills, continuing across bridge past Stop 8a and to the right on paved road toward Springfield.

60.9 Park. Proceed westerly across north end of field past small cottage to STOP 11 at contact between garnetiferous phyllite of Waits River Formation and "garbenschiefer" with large garnets. This locality is, perhaps, the best locality for seeing evidence of both Events I and II within a single rotated garnet. A stereoscopic photograph of a rotated garnet you will see at this locality appears as figure 14-3 in Rosenfeld, 1968, p. 192. A discussion of the generation of the central surface of garnets at this locality is found in Rosenfeld, 1970, p. 40. Trip ends here. Return to Keene via Rtes 103, 5 to Bellows Falls, and then 12.